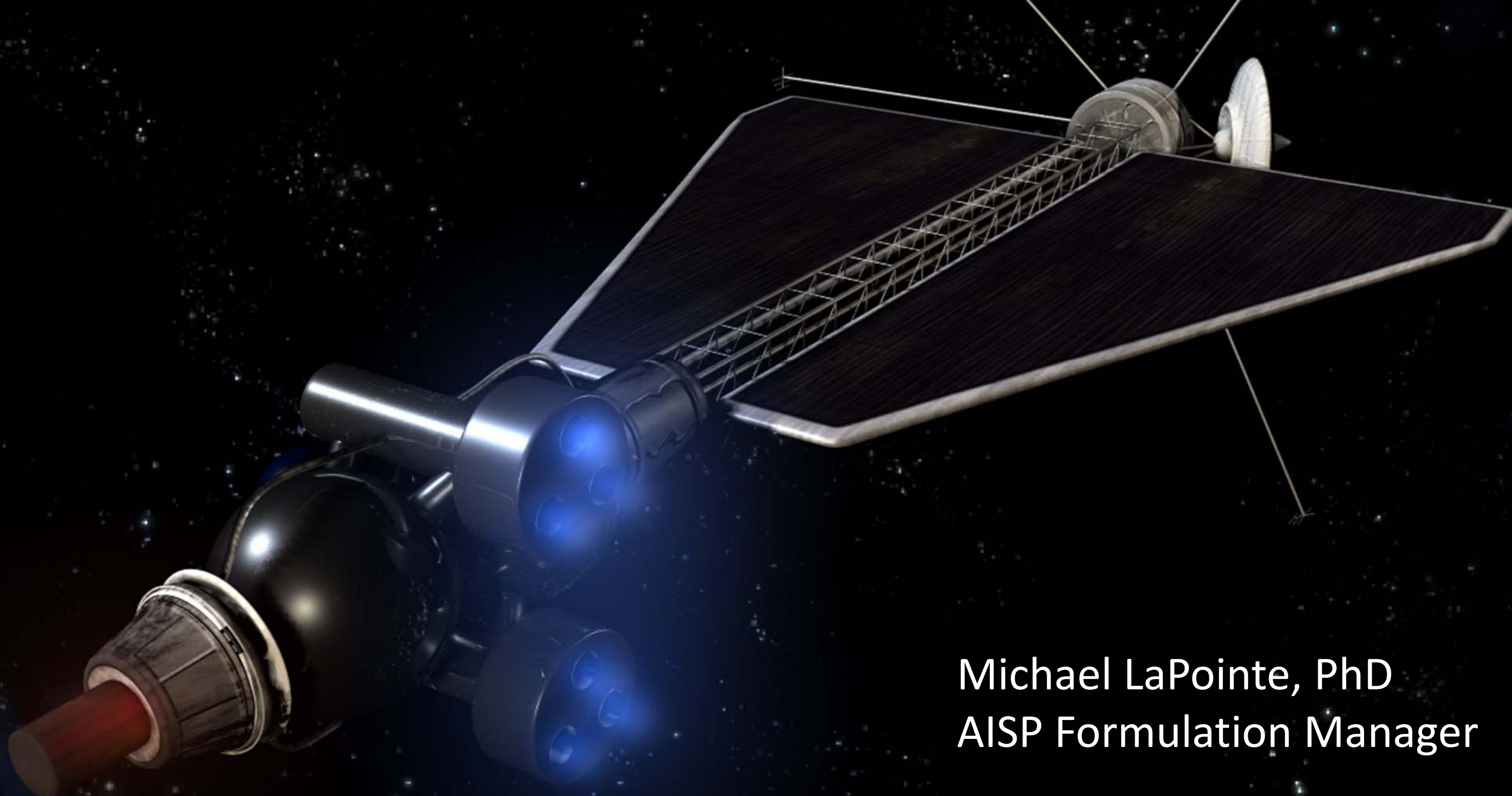
OVERVIEW OF THE NASA ADVANCED IN-SPACE PROPULSION PROJECT



Michael LaPointe, PhD
AISP Formulation Manager

JANNAF Meeting
December 5-9, 2011
Huntsville, Alabama

Background: FY11 NASA ETDD Program

In FY11, NASA established the Enabling Technologies Development and Demonstration (ETDD) Program, a follow on to the earlier Exploration Technology Development Program (ETDP) within the NASA Exploration Systems Mission Directorate

- **Objective: Develop, mature and test enabling technologies for human space exploration**
  - **Develop and demonstrate prototype systems** to feed NASA Flagship, robotic precursor, and other exploration goals
  - **Develop long-range, critical technologies** to provide the foundation for a broad set of future space exploration capabilities
  - **Provide an infusion path** for promising, game-changing technologies developed by the NASA OCT Space Technology Program
  - **Assess the feasibility** of system and operational concepts resulting from architectural studies by building and testing proof of concept systems
  - **Develop exploration technologies** that may also have terrestrial applications for clean energy and environmental protection

FY11 ETDD Demo and Foundational Projects

To meet these objectives, ETDD structured a combination of Demonstration Projects and Foundational Domain Projects*

- **Demonstration Projects**: integrate multiple technologies into prototype systems for validation in a relevant environment
- **Foundational Domain Projects**: advance SOA in key technical disciplines, supply mature technologies to ETDD Demo and agency projects, and manage a diverse portfolio of both long-range and focused development

- **Demonstration Projects**
  - Lunar volatiles
  - High power electric propulsion
  - Autonomous precision landing
  - Human exploration technologies
  - Fission power systems
- **Foundational Domain Projects**
  - →Advanced In-Space Propulsion (AISP)
  - Autonomous Systems and Avionics
  - Cryogenic Propellant Storage and Transfer
  - Entry, Descent and Landing Technology
  - EVA Technology
  - High Efficiency Space Power Systems
  - Human-Robotic Systems
  - In-Situ Resource Utilization
  - Life Support and Habitation Systems
  - Lightweight Spacecraft Materials & Structures

*** *ETDD Program content was later restructured in FY11 due to budgetary & programmatic requirements***

AISP Foundational Domain Project

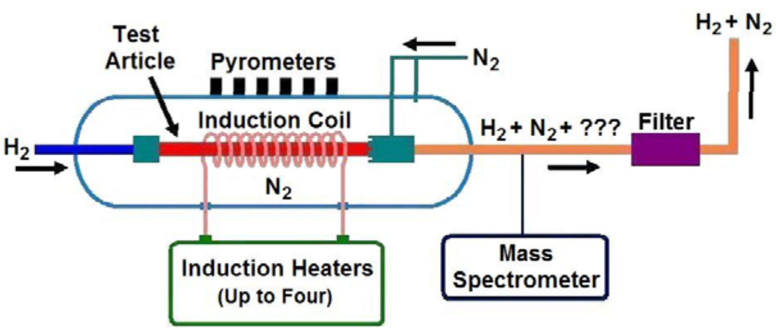
- **<u>AISP Project Charter</u>:** “NASA will conduct foundational research, study the requirements, and develop design concepts for advanced high-energy, in-space propulsion systems to support deep-space human exploration (crew and cargo) and reduce travel time between Earth’s orbit and future destinations for human activity. These technologies could include nuclear thermal propulsion, solar and nuclear electric propulsion, plasma propulsion, and other high-energy and/or high-efficiency propulsion concepts.”
- **<u>FY11 Focus Areas</u>:**
  - Nuclear thermal propulsion (NTP)
  - High power electric propulsion (EP)
- **<u>FY11 Resources</u>:**
  - Planned: $8.1M procurement/travel plus 20 FTE (civil servants)
  - Subsequently designated a “new start” under FY11 continuing resolution
  - Actual: $7.75M (full cost; includes procurement, travel and 4.6 FTE)
    - About 10% went to AISP Project/NASA Center management costs
    - Remaining funds split approximately 60/40 between NTP and EP activities

SELECTED HIGHLIGHTS

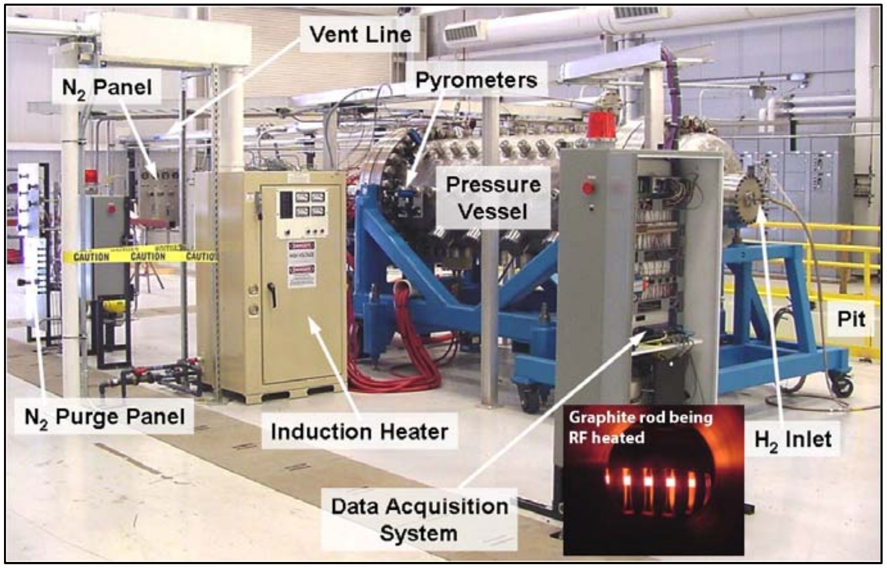
NTREES Test Facility

Nuclear Thermal Rocket Element Environmental Simulator (MSFC)

- Test articles mounted in the simulator are inductively heated to accurately reproduce prototypic temperatures and heat fluxes
- Simulates the environmental conditions (minus the radiation) to which NTP fuel elements and materials will be subjected during operation
  - Capable of testing with a variety of propellants (H2, H2 + additives, etc)
  - Facility is currently licensed to test fuels containing depleted uranium



Operational Parameter	Value
Maximum Test Article Temperature (K)	> 3000
Current Power Capability (kW)	Up to 50
Max Expandable Power Capability (kW)	Up to 3500
Maximum Test Article Length (m)	2.50
Maximum Test Article Diameter (m)	0.30



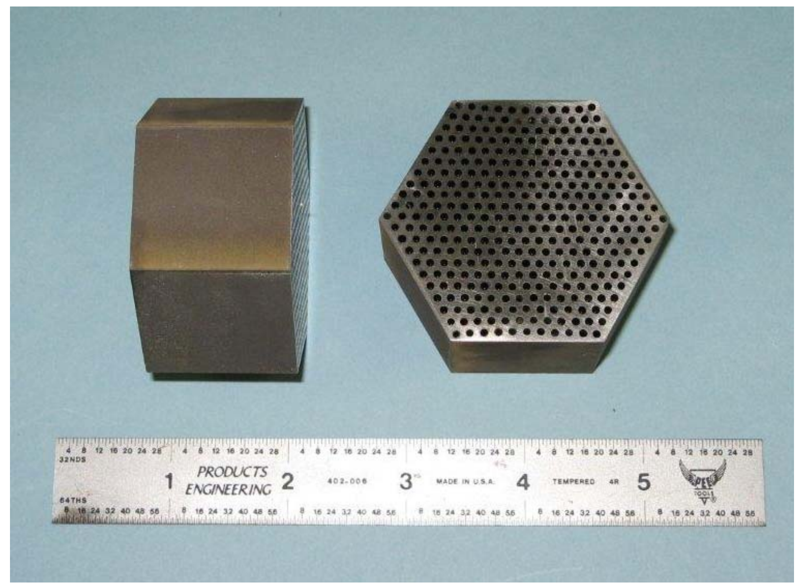
NTP Fuel Element Fabrication Techniques

Simulated Nuclear Fuel Element Fabrication (MSFC, DOE)

- Investigate fabrication techniques using surrogate materials such as W, W-HfN, leading to sample fabrication with depleted uranium
- Demonstrate pulsed electric current & hot isostatic pressing sintering methods
- Goal is to screen samples in NTREES to investigate material properties, etc.

NTP CERMET Sample Element (W-HfN)
(19 Channels, 1" Diameter x 2" Long)

NTP CERMET Sample Element (W-HfN)
(19 Channels, 1" Diameter x 12" Long)



NTP CERMET Sample Element
(331-channels, W surrogate)

NASA-Funded DOE NTP Work Plan (CY11)

DOE Objectives

- **Mission Analysis, Engine/Stage System Characterization & Requirements Def.**
  - *Define requirements and system characteristics (engine, stage, and vehicle) for future human missions to guide concept design & development for a ground demo & flight technology demonstrator mission*
- **NTP Fuels and Coatings Assessment and Technology Development Plan**
  - *Validate, mature and recertify two primary fuel forms identified by NASA and DOE: NERVA carbide "composite" and UO_2 in tungsten ceramic metallic (Cermet) fuel*
- **Engine Conceptual Design and Analysis, Model Development**
  - *Develop and analyze engine conceptual designs with NERVA and Cermet-based fuels using state-of-the-art NASA and DOE models and analysis*
- **Approaches for Affordable Ground Testing**
  - *Develop innovative approaches to NTP ground testing requiring modest supporting infrastructure that offer the potential for reduced development costs*
- **Formulation of Affordable and Sustainable NTP Development Strategy**
  - *Develop a joint NASA / DOE program plan and formulate a development strategy that allows an affordable NTP development program*

DOE Deliverables

- **Interim and final reports**, including detailed analysis and program plans

Interim NTP Analysis Status (GRC, DOE)

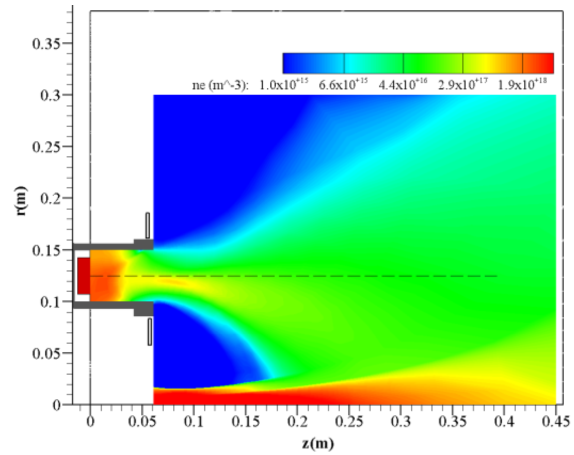
- **GRC NTP Mission Analysis Code** updated to perform fast parametric analysis, allowing quicker NTP scoping studies for various mission requirements
- **Nuclear Engine System Simulation (NESS) code** updated to analyze smaller NERVA-derived engines (25-klbf to 5-klbf) to determine performance and mass of smaller engines for flight technology demonstrator missions
  - Preliminary analysis completed for a simple 1-burn lunar flyby 5-klbf FTD mission
- **Preliminary Monte Carlo Neutron Photon (MCNP) core design** for small NERVA-derived engines provided DOE INL; input is being used to support multi-physics modeling of small engine mass and performance
  - Evaluating new core arrangements of tie tubes and fuel elements
- **Preliminary analysis for performing SAFE** (Subsurface Active Filtration of Exhaust) ground testing at the Nevada National Security Site completed in collaboration with National Security Technologies; report in preparation
- **NTP development strategy** is building on past data, detailed computational analysis, focused non-nuclear & nuclear tests, limited ground & flight testing

Note: Additional NASA-funded industry studies are underway (Aerojet; Pratt-Whitney Rocketdyne), each $250k for 6 months. Independent analysis of NTP requirements/plans; awaiting final reports

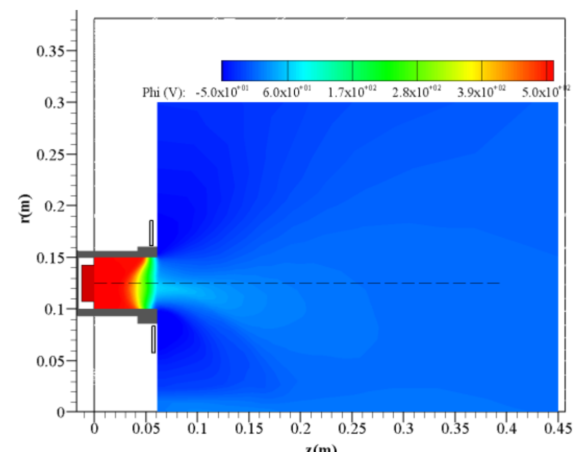
Electric Propulsion Thruster Modeling

Hall2De Thruster Code (JPL)

- Operational and in use at both JPL and GRC
- Preliminary simulations of the NASA-300M 20-kW Hall thruster at 500 V and 40 A predicted 0.98 N thrust, in good agreement with the measured value of 1.02 N
- Currently being being used to predict the performance of the NASA-457M 50-kW Hall thruster, and will also be used to help design higher power Hall thrusters
- Hall2De is also being used to assess power deposition to the channel walls of the H6 6-kW Hall thruster for magnetically shielded and unshielded configurations
  - Anticipate significantly lower erosion rates in magnetically-shielded configuration; will validate with experimental testing



Density

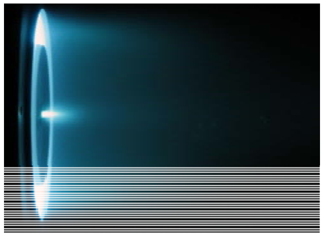


Potential

OrCa2D Cathode Model (JPL)

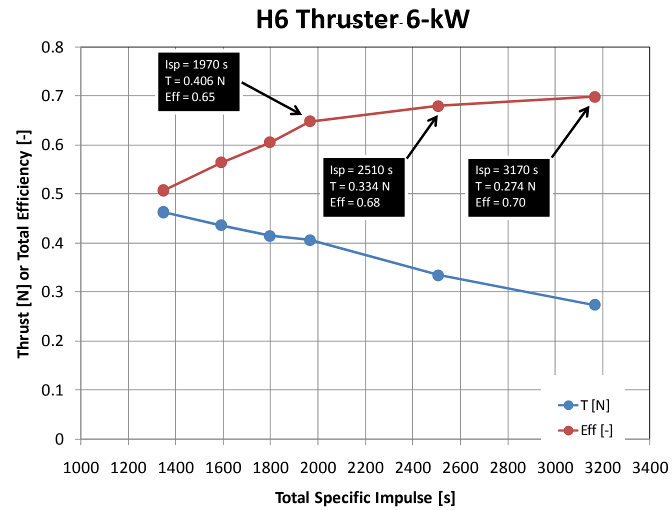
- Updated to incorporate a new cold start modeling capability for neutral gas, and plasma and emission cold start modeling capabilities

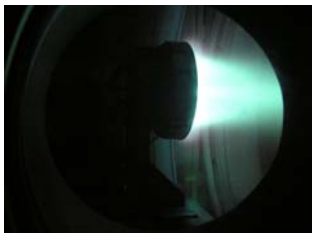
High Power Hall Thruster Development



H6 6-kW$_e$ Hall thruster (JPL)

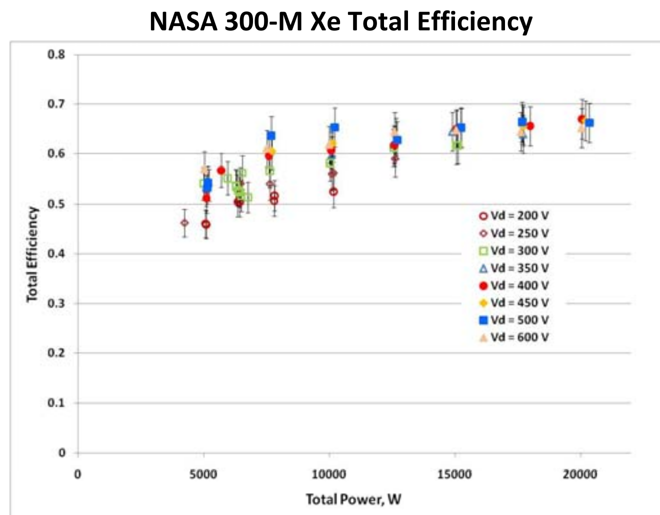
- Achieved 70% total efficiency, highest ever measured for a Hall thruster
- Being used to experimentally validate thruster magnetic shielding designs





NASA-300M Hall thruster (GRC)

- Peak total efficiency of ~67% achieved at 500 V and 20 kW
- Peak Isp ~2,920 sec at 600 V and 20 kW
- Data being used to validate Hall2De code



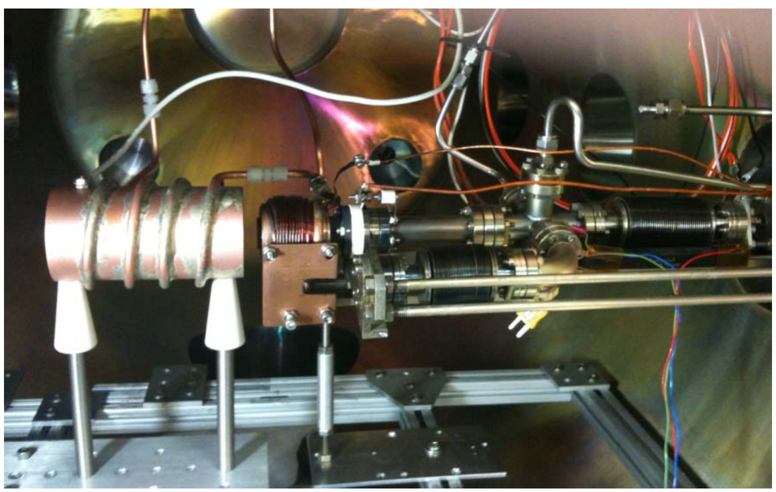
NASA-457Mv2 Hall thruster (GRC)

- Limited FY11 testing, but operated up to 70-kW$_e$ in prior test program
- 50-kW operation with detailed diagnostics in VF5 main chamber planned in CY11

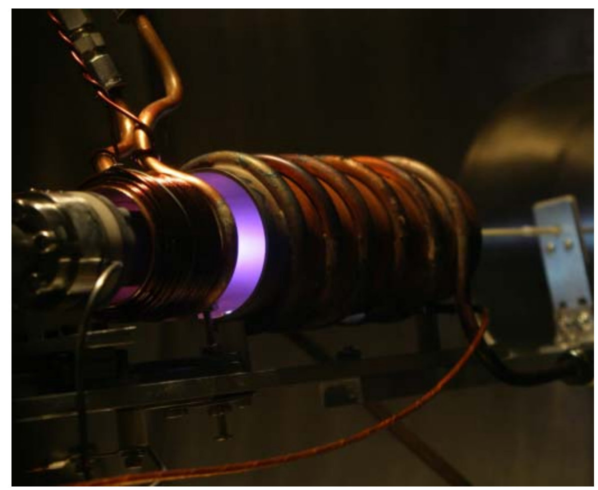
High Current Cathode Development

High current (250-A) LaH6 hollow cathodes (JPL)

- Required for several candidate high power EP thruster systems
- Cathode test facility at JPL used for performance testing, code validation
  - Completed full plasma characterization at 100-A (internal density, temperature and potential profiles)
  - Operation of high current cathode with larger insert diameter, graphite keeper and tungsten orifice plate has been demonstrated from 20-A to 250-A
- Long duration degradation testing to be performed at MSFC



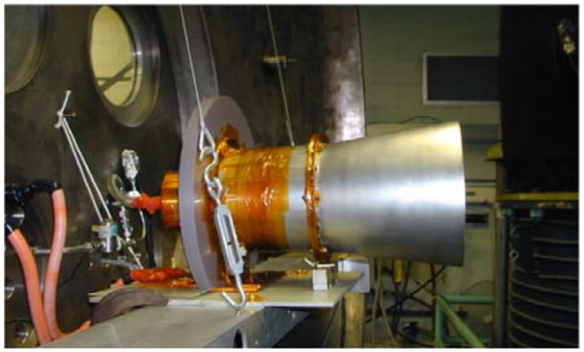
JPL LaB6 cathode test facility

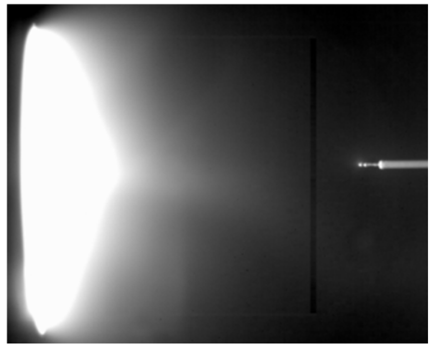


60-A cathode testing in the JPL facility

Advanced EP Concepts

Magnetoplasmadynamic (MPD) Thruster





JPL quasi-steady MPD Thruster anode (left); plasma discharge (right)

JPL investigating quasi-steady applied field MPD thrusters to determine the effect of an applied magnetic field in suppressing the onset of high current instabilities (Cal Tech dissertation). GRC bringing pulsed MPD facility back online.

Pulsed Inductive Thruster (PIT)

MSFC rapid-prototype PIT on thrust stand (left); pre-ionization plasma discharge (right)

MSFC investigating variants of pulsed inductive thruster designs and propellant pre-ionization techniques to evaluate scaling parameters and improve thruster efficiency (Princeton U. dissertation).

High Power PPU

High power Hall PPU roadmap development (GRC)

- SOA PPUs:
  - Biggest PPU ever built processes 7 kW (NEXT ion thruster)
  - Biggest power module ever built processes 2 kW (BPT-4000 Hall thruster)
  - Highest input voltage used in a PPU is 160 V (NEXT, NSTAR ion thrusters)
  - Highest efficiency of a discharge supply is 96% (HiVHAC 1-KW BB Hall thruster)
  - Lowest specific mass for a Hall thruster PPU is 2.8 kg/kW (BPT-4000 Hall thruster)
- Goals identified for 20-50kW PPU:
  - 97% peak efficiency and ≤ 2 kg/kW specific mass
  - High input voltage to accommodate high power missions
  - Low parts count for low cost and reliability
- GRC initiated a trade study on high power converters, developed power loss and mass models to support trade study, and performed limited component testing to validate models
- Result is a tool to predict component performance for a specific design solution, and to evaluate new components from a rapidly evolving semiconductor industry

Additional Activities

Additional activities carried out in FY11

- **Nested channel hall thrusters**
  - JPL thermal analysis of X3-80 thruster design
  - Design of high current LaB6 cathode to be provided for X3-80 testing
  - GRC hardware and diagnostics development in collaboration with AFRL
- **Advanced in-situ erosion diagnostics**
  - Surface layer activation (JPL)
  - Fiber optic regression probe (MSFC)
- **GRC COMPASS MW-class NEP Mars cargo mission analysis**
  - Led by the ETDD High Energy Space Power Systems Project (GRC)
  - 100-mT cargo delivery for NASA Mars DRA-5.0 split crew-cargo mission
  - Evaluated nuclear power system designs, 2 high power electric propulsion options
    - 100-kW Hall thruster based on NASA 457Mv2 design; 10+2 configuration
    - 125-kW VASIMR thruster based on current lab model; 4 x 2-thruster modules
  - Compared to baseline NTP, reduced number of cargo launch vehicles from 3 to 1
  - Required launching 1 to 2 conjunction class mission cycles earlier than crew launch

Primary FY11 Responsibilities by Organization

Nuclear Thermal Propulsion:

MSFC
- Complete and commission the NTREES 50-kW test facility
- Development of NTP fuel element and coating fabrication techniques

GRC
- Oversight of DOE tasks and industry contracts
- Mission analysis and support of HEFT architectures
- NTP engine design & modeling

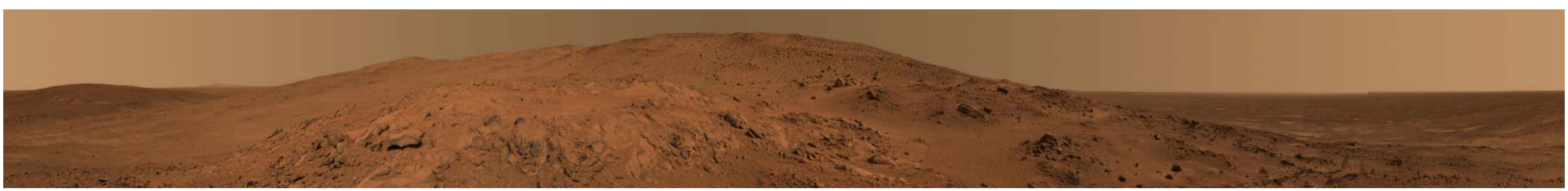
DOE/Industry
- Mission analysis, engine/stage system characterization, requirements def
- NTP fuels and coatings assessment and technology development plan
- Engine conceptual design & analysis
- Approaches for affordable ground testing
- Affordable/sustainable development strategy

High Power Electric Propulsion:

MSFC
- Rapid prototype PIT development
- In situ thruster erosion techniques
- Long duration LaB6 cathode test

GRC
- PPU Roadmap
- Hall thruster modeling
- 20-kW Hall thruster test
- 50-kW Hall thruster test
- Nested channel Hall thrusters
- MW-EP Mars mission analysis

JPL
- Hall thruster modeling
- High current hollow cathode modeling
- High current LaB6 cathode testing
- Hall thruster magnetic shielding (H6)
- Nested channel Hall thruster analysis
- Applied-field quasi-steady MPD



AISP Papers and Publications

AIAA-2011-5518: "Mass and Cost Model for Selecting Thruster Size in High-Power Electric Propulsion Systems"; R. Hofer, J. Polk, D. Goebel, I. Mikellides, I. Katz, J. Snyder, J. Brophy, R. Reeve, T. Randolph, N. Strange, D. Landau, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

AIAA-2011-5521: "Performance Evaluation of the NASA-300M 20 kW Hall Thruster"; H. Kamhawi, NASA Glenn Research Center, Cleveland, OH

AIAA-2011-5809: "Design of a Laboratory Hall Thruster With Magnetically Shielded Channel Walls for Long Life"; I. Mikellides, I. Katz, R. Hofer, D. Goebel, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

AIAA-2011-5846: "Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design"; B. Schnitzler, Idaho National Laboratory, Idaho Falls, ID; S. Borowski, NASA Glenn Research Center, Cleveland, OH; J. Fittje, Analex Corporation, Cleveland, OH

AIAA-2011-5847: "Recapturing NERVA-Derived Fuels for Nuclear Thermal Propulsion"; A. Qualls, G. Flanagan, G. Bell, Oak Ridge National Laboratory, Oak Ridge, TN

AIAA-2011-5945: "A Rational Strategy for Nuclear Thermal Rocket Development"; S. Bhattacharyya, RENMAR Enterprises, Inc., N. Augusta, SC

AIAA-2011-5947: "Conceptual Design of a CERMET NTR Fission Core Using Multiphysics Modeling Techniques"; J. Webb, Center for Space Nuclear Research, Idaho Falls, ID

AIAA-2011-6067: "Pulsed Electric Propulsion Thrust Stand Calibration Method"; A. Wong, K. Polzin, J. Pearson, NASA Marshall Space Flight Center, Huntsville, AL

AIAA-2011-6068: "Thrust Stand Measurements of the Microwave Assisted Discharge Inductive Plasma Accelerator"; A. Hallock, Princeton University, Princeton, NJ; K. Polzin, NASA Marshall Space Flight Center, Huntsville, AL; G. Emsellem, Elwing Company, Irvine, CA

AIAA-2011-6082: "Channel Wall Plasma Thermal Loads in Hall Effect Thrusters with Magnetic Shielding"; I. Katz, I. Mikellides, D. Goebel, R. Hofer, J. Polk, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

Oral Presentation: "Nuclear Thermal Propulsion: A Proven Game-Changing Growth Technology for Future NASA Exploration Missions"; S. Borowski, D. McCurdy, T. Packard, NASA Glenn Research Center, Cleveland, OH

Oral Presentation: "Approaches to Address Challenges of Flying Affordable Nuclear Thermal Propulsion Systems for Exploration"; J. Werner, Idaho National Laboratory, Idaho Falls, ID

Space 2011: "MW-Class Electric Propulsion System Designs for Mars Cargo Transport," J, Gilland, M. LaPointe, S. Oleson, C. Mercer, E, Pencil, L. Mason

JANNAF 2011: Multiple; see JANNAF Meeting Program

AISP Project Status

- **AISP Project formally ended on September 30, 2011**
- **NASA NTP work** is currently being performed under the Advanced Exploration Systems (AES) Program within the NASA Advanced Capabilities Office
  - Nuclear Cryogenic Propulsion Stage Project (PM: Mike Houts, MSFC)
    - Includes engine system modeling, completion of MW-class NTREES, fabrication and testing of sample fuel elements, and continuing refinement of an affordable NTP development and qualification strategy
  - Possibility of funding under the NASA OCT Nuclear Systems Project > FY12
- **NASA High Power EP work** is currently being performed under the Office of Chief Technologist, Space Technologies Program
  - In-Space Propulsion Project (PM: Tim Smith, GRC)
  - Discussed in this session, “Overview of NASA FY12-14 OCT Activities”

Note: NASA Science Mission Directorate EP activities are also discussed in this session, “Status of NASA In-Space Propulsion Technologies and Their Infusion Potential”, D. Anderson, E. Pencil, et al.

Acknowledgements

The FY11 AISP Project was funded through the NASA Enabling Technologies Development and Demonstration Program, whose support is gratefully acknowledged

For additional information:

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Related JANNAF Sessions:

- **Tuesday, Dec 6, 1:30-6PM (Atlantis)**
  ELECTRIC PROPULSION DIAGNOSTICS, EVALUATION, AND MODELING
- **Wednesday, Dec 7, 8:00-11:30AM (Atlantis)**
  ADVANCED ELECTRIC PROPULSION
- **Wednesday, Dec 7, 1:30-6PM (Atlantis)**
  NUCLEAR PROPULSION AND POWER
- **Thursday, Dec 8, 1:30-4:30PM (Atlantis)**
  HIGH-POWER HALL THRUSTERS